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PROPOSED GRAVITY-GRADIENT DYNAMICS EXPERIMENTS IN LUNAR ORBIT USING THE RAE-B SPACECRAFT

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GREENBELT, MARYLAND

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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ABSTRACT

A series of seven gravity-gradient dynamics experiments is proposed utilizing the Radio Astronomy Explorer (RAE-B) spacecraft in lunar orbit (launch is currently scheduled for June 1973). It is believed that none of the experiments will impair the spacecraft structure or adversely affect the continuation of the scientific mission of the satellite. The first experiment is designed to investigate the spacecraft dynamical behavior in the absence of libration damper action and inertia. It requires stable gravity-gradient capture of the spacecraft in lunar orbit with small amplitude attitude librations as a prerequisite. Four subsequent experiments involve partial retraction, ultimately followed by full re-deployment, of one or two of the 230-meter booms forming the lunar-directed Vee-antenna. These boom length change operations will induce moderate amplitude angular librations of the spacecraft. Observations of the dynamical motions will permit long-term study of the particular asymmetric or semi-symmetric spacecraft configuration, providing improvements in the laboratory estimates of spacecraft mechanical and physical parameters. A sixth experiment involves a pitch inversion of the spacecraft through similar variations in the spacecraft moments of inertia. This operation would provide a "new" antenna array directed toward the celestial sphere to verify previously observed radio astronomy measurements. The final experiment in gravity-gradient controls is dependent upon mission conditions existing at the time and is more general in character. The series of experiments proposed follows as a sequel to a similar set of dynamics experiments successfully conducted in 1970 through 1972 utilizing the RAE-I spacecraft in Earth orbit. Dynamical in-orbit observations recorded during the RAE-I experiments are presented when applicable to the proposed RAE-B experiments, especially regarding anticipated spacecraft behavior. As a result of the performance of the proposed experiments and a thorough analysis of the observational data, information generally applicable to advancing current understanding of passive three-axis gravity-gradient stabilization and control systems will be forthcoming. This could be of significant value in the design and planning of future missions involving large gravity-stabilized arrays.

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PROPOSED GRAVITY-GRADIENT DYNAMICS EXPERIMENTS IN LUNAR ORBIT USING THE RAE-B SPACECRAFT

INTRODUCTION

It is the purpose of this document to propose a series of gravity-gradient dynamics experiments utilizing the Radio Astronomy Explorer (RAE-B) spacecraft when it achieves the planned lunar orbit. The RAE-B lunar mission, currently scheduled for a mid-1973 launch, is designed to place a spacecraft into orbit about the moon to measure, with directivity, the intensity of radio signals from celestial sources as a function of frequency, direction, and time (Reference 1). The spacecraft will provide mapping of the galaxy at selected frequencies in the range from 0.03 to 20 MHz free from the perturbing effects of the terrestrial ionosphere. To this end, the disc of the moon will be used for occultation, focusing, or aperture blocking for increased resolution and discrimination of radio emissions.

The series of dynamics experiments described herein follows as a sequel to a similar set of dynamics experiments proposed (Reference 2) in 1970 and successfully conducted the following year after the first Radio Astronomy Explorer (RAE-I; Explorer 38) had achieved a gravity-stabilized Earth orbit and more than fulfilled its scientific mission objectives. A summary of the series of gravity-gradient dynamics experiments performed in Earth orbit using the RAE-I spacecraft appears in Table 1. A description of the operational aspects of the performance of these dynamics experiments has been presented previously (Reference 3). The dynamical data relating to spacecraft behavior during these experiments have undergone a thorough analysis, and the results of the post-experiment studies have also been presented (References 4, 5, and 6). A brief listing of the most significant results of the in-orbit gravity-gradient dynamics experiments performed with the RAE-I spacecraft follows:

- (1) Increased confidence has been generated in the validity and adequacy of the computer simulations and analytical techniques used to model the spacecraft dynamics;
- (2) The RAE-I on-board damper system has demonstrated in orbit significant capabilities for reducing large amplitude attitude oscillations;
- (3) The damper system is only marginally useful in maintaining dynamical stability under near-equilibrium conditions, in accordance with its design criteria;

Table 1

Summary of Gravity-Gradient Dynamics Experiments* Performed
in Earth Orbit Using the RAE-I Spacecraft

Dynamics Experiment		Dates of Performance	Status
Type	Description		
Damper Clamping	Full sunlight conditions	Dec. 1, 1970 to Dec. 7, 1970	Damper de-activated for 6.03 days while spacecraft in continuous sunlight.
	Partial solar shadowing	June 14, 1971 to June 21, 1971	Damper de-activated for 6.34 days while spacecraft within solar shadow 19 to 25 minutes per 225-minute orbital period.
Single Lower Leading Boom Operations	Partial retraction to 165-meter length	Jan. 18, 1971	Damper active throughout experiment. Spacecraft in continuous sunlight.
	Full re-deployment to 230-meter length	Jan. 25, 1971	Damper de-activated for initial 29 hours. Spacecraft in continuous sunlight until Feb. 26, 1971.
Double Lower Boom Operations	Partial retraction to 200-meter lengths	Dec. 7, 1971	Damper de-activated for initial 48 hours. Spacecraft in continuous sunlight.
	Full re-deployment to 230-meter lengths	Dec. 15, 1971	Damper active throughout experiment. Spacecraft in continuous sunlight until Jan. 18, 1972.

*The pitch inversion operation performed with the RAE-I spacecraft on October 31, 1972, is considered and discussed separately; see Figure 1 and accompanying text.

- (4) The damper system appears more effective for certain asymmetrical spacecraft configurations than for the fully symmetrical (nominal) mode;
- (5) The spacecraft has demonstrated dynamical stability in three distinct configurations (fully symmetrical, semi-symmetrical, and asymmetrical), thereby providing more than ample validation of its gravity-gradient control design;

- (6) External in-orbit disturbances on the spacecraft, including the thermal gradients across the booms, are virtually negligible;
- (7) The capability of the RAE-I spacecraft to survive and recover from adverse dynamical situations has been demonstrated;
- (8) The on-board mechanical and electrical systems have been shown to perform satisfactorily and reliably even after 3.5 years in the hostile space environment;
- (9) A non-linear coupling phenomenon between the pitch and yaw modes of oscillation that had been previously predicted on theoretical grounds has been observed in what is believed to be the first in-orbit demonstration of the effect;
- (10) The essential accuracy of ground-based measurements of the antenna boom and damper mechanical properties (with the possible exception of the effective semi-Vee angle of the booms) has been verified from in-orbit dynamical data; and
- (11) Increased confidence in the achievement of a successful RAE-B lunar mission has been generated.

It is anticipated that further refined analysis of the dynamical data gathered during these dynamics experiments, including studies currently in progress, will produce additional significant results. In particular, it is hoped that improved estimates of the in-orbit values of several pertinent spacecraft mechanical parameters, such as the thermal gradients across the antenna boom cross sections and the flexural rigidity of the booms, will result.

In addition to the successful series of dynamics experiments performed in 1970 and 1971 briefly described above, the RAE-I spacecraft was utilized to perform a pitch inversion maneuver on October 31, 1972. This ambitious operation, described in a preliminary paper (Reference 7), was conducted in order to provide an opportunity for use of the original Earth-directed antenna booms in viewing radio emissions from celestial sources. A complementary objective of the inversion maneuver was to gain additional information on the stabilization and control of large gravity-gradient spacecraft arrays that would be valuable in RAE-B mission contingency planning. The method used for the spacecraft inversion, as illustrated in Figure 1, is dependent upon the physical principle of conservation of angular momentum. Carefully phased partial retractions of all four antenna booms simultaneously increased the usual orbital rotational pitch rate of the spacecraft to a rate at which inversion was achieved in less than one-half an

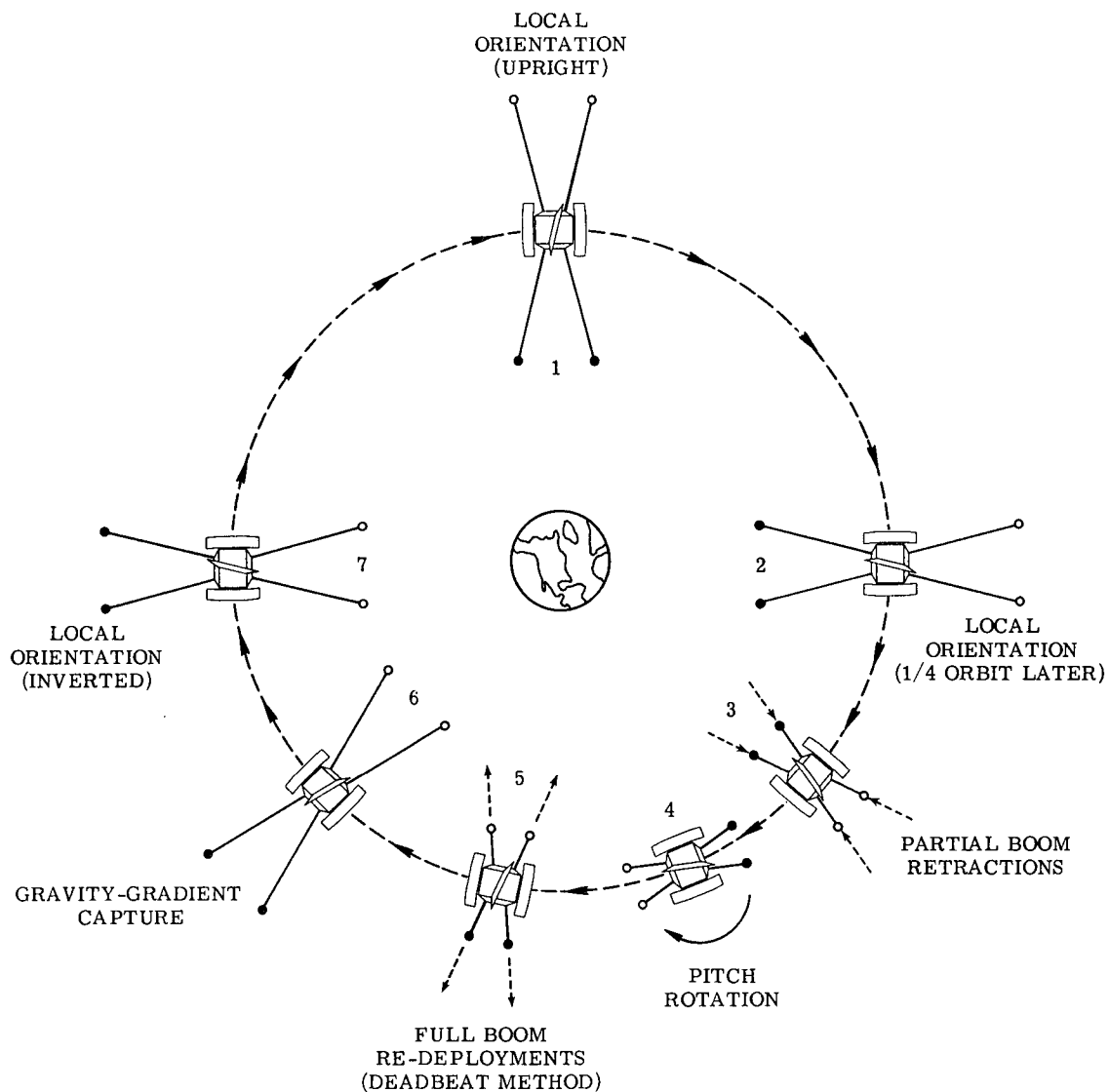


Figure 1. Method Used for Inversion of the RAE-I Spacecraft
on October 31, 1972

orbital period, i.e., in somewhat over 90 minutes. The partial retraction length used was 160 meters, and the damper was de-activated during the rotation interval. The four booms were re-deployed to full lengths just prior to completion of the 180-degree inversion in a so-called deadbeat technique. In this manner, the spacecraft was captured in the inverted position, and motions about the new local orientation were stable and well-bounded. The entire inversion operation was

completed as planned, with re-attainment of steady-state conditions in a matter of only several hours. The feasibility of gravity-gradient spacecraft control by active ground command was thus amply demonstrated.

OBJECTIVES OF THE EXPERIMENTS

The RAE-B spacecraft, as shown in Figure 2, consists of four highly flexible tubular antenna booms mounted in a double-Vee configuration with a rigid cylindrical spacecraft hub at the center. The four main radio frequency sensing antenna booms each extend approximately 230 meters (750 feet) from the hub center. The longitudinal dimensions of the spacecraft are greater than those of

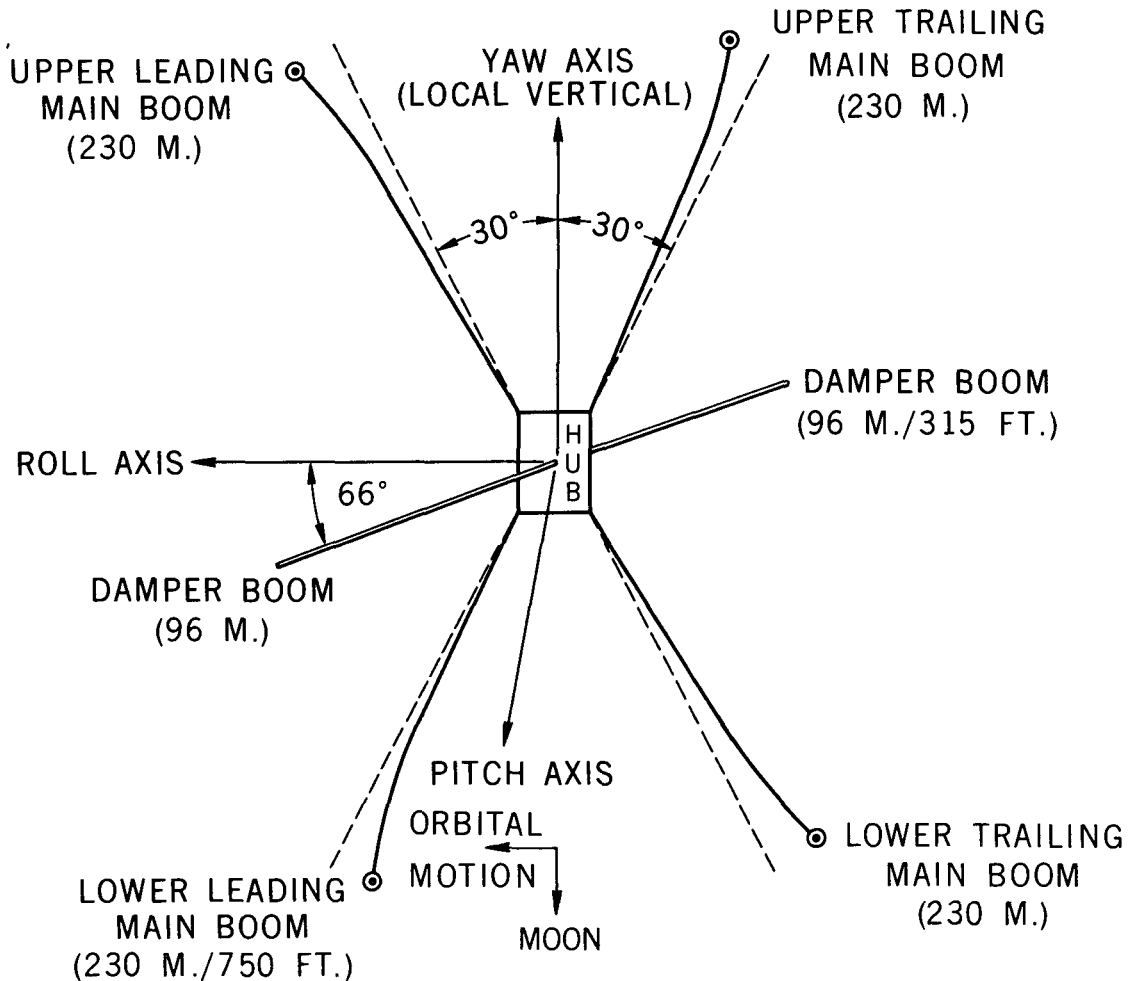


Figure 2. Basic Configuration of the RAE-B Spacecraft

any other array (excluding RAE-I) placed in space to date. Rotational oscillations of the spacecraft hub and the resulting indirect vibration of the primary antennas are attenuated by a magnetic hysteresis damper mechanism consisting in part of two additional damper booms, each 96 meters from hub center to tip. The damper booms operate with a single degree of freedom in a plane containing the nominal spacecraft hub local vertical axis and are skewed at an angle nominally designed to be approximately 66 degrees from the plane of the primary double-Vee antennas. This skew angle creates a bias of approximately 13 degrees in the spacecraft hub yaw equilibrium angle, as measured between the plane of the primary antennas and the orbital plane. Deflections of the flexible antenna booms from the straight-line locations are caused by a combination of static effects, due to gravity-gradient and inertial forces, and time-varying effects, due to thermal, solar, and orbital eccentricity perturbations.

The RAE-B spacecraft configuration, as described above and illustrated in Figure 2, is essentially identical to that of the RAE-I spacecraft launched into a near-circular Earth orbit at an altitude of nearly 6000 kilometers on July 4, 1968. Thus, the physical properties of the RAE-B spacecraft, currently undergoing laboratory measurement, are expected to be very similar to those of the predecessor spacecraft. In addition, the lunar orbital characteristics for the RAE-B mission (altitude of 1100 kilometers and orbital eccentricity of less than 0.005) were selected so as to duplicate as nearly as possible the gravitational environment of RAE-I. In particular, the orbital period of 225 minutes is to be identical for both spacecraft. Hence, the dynamical influences on the RAE-B spacecraft, despite the very different nature of its attracting primary center, should closely resemble those of the first spacecraft in the RAE series.

From the preceding introductory remarks, the motivation for performing a set of gravity-gradient dynamics experiments utilizing the RAE-B spacecraft is virtually apparent. The general reasons for conducting a series of experiments are summarized as follows:

- (1) The study of very long-term dynamical stability in the absence of an active libration damper system is possible with the RAE-B spacecraft for the first time. On the lunar spacecraft, the damper booms may be retained in the undeployed configuration, or, once deployed, they may be retracted partially or fully. By contrast, the RAE-I libration damper booms, once deployed, could not be retracted. Furthermore, in order to maintain the RAE-I damper in the clamped, or de-activated, condition, continuous and extensive use of on-board electrical power is required.
- (2) The RAE-B spacecraft in a configuration with retracted (or undeployed) damper booms will provide a planar distribution of mass that coincides

with the orbital plane. In addition to providing a new and different configuration for gravity-gradient dynamical study, the elimination of a yaw bias under equilibrium conditions and the removal of secondary booms projecting onto the plane of the primary Vee-antennas are highly desirable attributes from the standpoint of radio astronomy observation.

- (3) Observations of the RAE-B spacecraft dynamical motions induced by partial boom retractions and later re-deployments will enable improvements in the laboratory estimates of various spacecraft mechanical and physical parameters to be made through proper application of the mathematical models already available. In particular, the effective semi-Vee angles and the degree of flexure of the antenna booms are significant parameters in the reduction of radio astronomy data. Moderate amplitude librational motions are necessary in order to obtain meaningful results from the computer simulations used to model in-orbit dynamical behavior.
- (4) The studies of the RAE-B dynamical motions and improvement of the system physical parameters would permit comparisons with similar results achieved for the RAE-I spacecraft system, thereby providing a measure of consistency between sequential satellites of the same series with nearly identical design.
- (5) Information gained from an analysis of the experimental results will be generally applicable to advancing the current state of knowledge of passive three-axis gravity-gradient spacecraft stabilization systems. In particular, the dynamics experiments will demonstrate the use of a gravity-gradient system (which is, under nominal circumstances, a totally passive attitude control system) in an active control mode of operation. Such uses could be of significant value in the planning of future applications to large gravity-stabilized arrays.

DESCRIPTION OF THE EXPERIMENTS

The gravity-gradient dynamics experiments described below are intended, in large part, to perturb the steady-state spacecraft librational motions under in-orbit equilibrium conditions, but always with minimal risk to the spacecraft structure and with due consideration to the continuation of the scientific mission. As shown in summarized form in Table 2, a series of six specific dynamics experiments, following the required main boom deployments to achieve full mission status, are proposed, with one additional more general dynamics experiment to be performed subsequently if conditions warrant. Each of the experiments listed in Table 2 will be discussed individually in the following text, including a description of the experiment, its purpose, and an estimate of the anticipated dynamical behavior of the spacecraft as a result of performance of the experiment. A general

Table 2

Summary of Gravity-Gradient Dynamics Experiments to be Performed
in Lunar Orbit Using the RAE-B Spacecraft

Dynamics Experiment		Duration	Remarks
Type	Description		
Nominal Mission Events	Main antenna boom deployments	Several days to two weeks for two-step sequence	Required to achieve full mission status. Double deadbeat method will be used.
Absence of Damper Action	Non-deployment (or full retraction) of damper	Open-ended	Stable orbital capture with small librations is a prerequisite. Permits long-term study of stability in planar configuration.
Single Lower Boom Operations	Partial retraction	One to six months	Long-term asymmetric configuration will induce moderate amplitude librations.
	Full re-deployment		Proper phasing of re-deployment will reduce residual librations.
Double Lower Boom Operations	Partial retraction	One to six months	Long-term semi-symmetric configuration will induce moderate to large amplitude librations.
	Full re-deployment		Proper phasing of re-deployment will reduce residual librations.
Spacecraft Inversion In Pitch	Partial retractions followed by full re-deployments of all main booms	One to three hours; inverted position maintained thereafter	Proper phasing assures stable re-capture. Permits radio observations with new antenna array.
Gravity-Gradient Controls	Spacecraft reversion in yaw or spin up in pitch	Indefinite	Optional experiment to be performed following successful completion of above experiments.

discussion of the procedures to be followed in conducting the series of dynamics experiments will then be presented in the following section.

Experiment 0: Main Antenna Boom Deployments

This experiment involves deployment of the four primary Vee-antenna booms to full 230-meter lengths in a two-part deadbeat deployment sequence, similar to the method used during the RAE-I mission (Reference 8). This deployment sequence is designed to reduce residual librations about the equilibrium position, particularly in the pitch mode of oscillation, for in-orbit motions both at the intermediate lengths and at the final lengths. Since deployment of the main booms is required to obtain a useful antenna array for radio astronomy observations, this is not an optional experiment but is included in the nominal spacecraft sequences to achieve full scientific mission status (Reference 1). Present intentions in the RAE-B deployment sequence are to adjust the spacecraft attitude prior to deployment so that the spin axis is in the orbital plane and parallel to the local vertical axis and to despin, by means of the attitude control system, to a rate of 0.25 revolutions/minute. The initial deadbeat deployment to intermediate boom lengths of 183 meters will then proceed in two stages, with initiation of boom extension at selected times based upon the achievement of specified attitude angles (within certain tolerances known as attitude "windows"). After orbital capture at the intermediate boom lengths occurs, the spacecraft operation will be monitored for approximately one week (or possibly for a longer duration). During this interval, radio emissions will be observed with use of the RAE-B dipole antenna. When this monitoring interval is concluded, the main antennas will be deployed to full 230-meter lengths in a double deadbeat sequence, in which the upper and lower Vee-antenna booms are deployed sequentially, rather than simultaneously, by the deadbeat method.

The purposes of the main antenna boom deployments are clearly to achieve gravity-gradient capture in lunar orbit and to permit directive radio astronomy observations with the stabilized antenna array. Residual librations about the equilibrium position are nominally to be confined to maximum excursions of ± 5 degrees in the roll and pitch modes and to ± 15 degrees in the yaw mode. It appears reasonable to categorize the nominal mission events consisting of the main antenna boom deployments as a dynamics experiment inasmuch as the dynamical data resulting from the initial boom deployments will prove to be of significant value in estimating such spacecraft mechanical parameters as the effective semi-Vee angles of the antennas and the degree of boom straightness. For this reason, it is important to gather a large volume of dynamical data during and immediately subsequent to the deployment operations. These data will consist of time histories of central hub attitude librations and of damper boom angular displacements (if the damper boom is deployed; see description of Experiment 1) as well as boom tip position information recorded by the antenna aspect system.

Considerable effort has been expended in study of the main boom deployments for the RAE-B mission by use of computer simulations of the dynamics (for example, Reference 9). The studies indicate that, barring hardware failure, the probability of successful deployment leading to gravity-gradient capture is very good. The successful deployment operations conducted during the RAE-I mission, following which the residual librations were well within the maximum angular bounds stated above, provide additional justification for this expectation.

Experiment 1: Non-Deployment (or Full Retraction) of the Libration Damper

This experiment involves, preferentially, retaining the damper booms in the undeployed configuration during and following the main antenna boom deployments as described above. The performance of this experiment presupposes that (1) the lunar orbit achieved for the RAE-B spacecraft is close to nominal, particularly with regard to the low orbital eccentricity (not to exceed 0.005) desired, and (2) the deployment operations result in a stable gravity-gradient capture with small residual librational motions (at most, ± 5 degrees in roll and pitch and ± 15 degrees in yaw about equilibrium values). An alternative form of this experiment, if deployment of the damper booms is required to assist in reducing the central hub librations or boom flexural deformations following main boom deployment operations, consists of full retraction of the damper booms at a later point in the mission when the above two prerequisites have been satisfied. Such an alternative form of this experiment might be recommended if the mission spacecraft sequence requires main boom deployment operations to be undertaken during partially solar shadowed orbits. Partial solar occultation of the spacecraft causes variations in the thermal forcing functions, thereby perturbing the satellite dynamical behavior in a manner that does not occur during full sunlight conditions. In either form of this dynamics experiment, the libration damper booms would remain in the undeployed (i.e., fully retracted) configuration for an open ended period of time depending upon the observed dynamical behavior of the spacecraft. If attitude librations were observed at some point during this experiment to exceed pre-selected angular bounds (chosen prior to initiation of the experiment), then the libration damper would be deployed as soon as practicable, and the dynamics experiment would then be considered concluded from an operational standpoint.

The primary purpose of this experiment is to permit a long-term study of dynamical stability with the spacecraft initially near equilibrium conditions and in the absence of libration damper inertia and action. The influences of relatively small amplitude forcing functions, arising from such effects as the thermal gradient across the main boom cross sections, non-zero orbital eccentricity, and solar pressure, can be observed over a long period of time in the increase of motions from the initial steady-state condition. The amount of structural damping

afforded by the flexibility of the main booms can be assessed from the rate of increase in librational motions, since such structural damping will provide the only means of energy removal from the spacecraft system during the experiment. If the system proves stable over the long term without benefit of damper action, the feasibility of stabilizing a large gravity-gradient spacecraft array by means of structural damping only will have been demonstrated. This would be a significant advance in current understanding of passive three-axis gravity-stabilized control systems. Furthermore, assuming the interval of damper inaction is of sufficient duration to include both full sunlight and partial solar occultation periods, additional information relating to solar and thermal perturbations caused by shadowing transients will be gained.

Secondary purposes of this experiment have been mentioned in the preceding section, with regard to the enhancement of radio astronomy observations. A spacecraft configuration with undeployed damper booms results in a mass distribution coinciding with the orbital plane. Hence, the otherwise non-zero yaw equilibrium bias (the value observed during the RAE-I mission was approximately -13 degrees) is eliminated, thereby simplifying the processing of astronomical data. Also, the opportunity to calibrate the Vee-antennas, without the perturbing non-planar effects of other lengthy booms extending from the spacecraft hub, would be an advantage for astronomical investigations. Finally, the existence of a planar mass distribution for the first time during gravity-gradient dynamics experiments would provide a fourth distinct array configuration for study.

An additional justification for non-deployment of the damper booms based on dynamical considerations, but exclusive of objectives of the proposed dynamics experiments, will now be presented. During the RAE-I mission, the primary antenna booms were deployed to full 230-meter lengths while the damper booms were extended to intermediate lengths of 85 meters (of the full 96-meter damper lengths). The deployment of the damper booms to full lengths was the final operation during the deployment sequences to attain full spacecraft mission status. However, the residual oscillations following the main boom deployments were sufficiently small that the change in principal spacecraft axes caused by the damper deployment operation introduced a noticeable increase in yaw librational motions (Reference 8). The librational motions of the spacecraft, subsequent to the damper deployment, then did decrease to steady-state values, thus indicating the effectiveness of the on-board damper system. Nonetheless, in the case that main boom deployments result in small amplitude residual librations, elimination of damper deployment will avoid causing a transient increase in attitude motions, particularly in the yaw mode. This advantage in non-deployment of the damper should be considered in conjunction with the other purposes for this dynamics experiment stated above.

The results from the damper clamping dynamics experiments utilizing the RAE-I spacecraft, as included in Table 1, indicate (References 5 and 6) that little system energy dissipation by the damper is required to maintain stability once the spacecraft has been brought near to equilibrium conditions, whether the satellite is experiencing continuous sunlight or partial solar shadowing. The attitude librations about three axes during the end of the second day and the beginning of the third day of damper clamping through partially shadowed orbits are shown in Figure 3. The non-periodic observed attitude data are not significantly different from observations recorded during steady-state conditions both before and after the dynamics experiment. That is, the well-stabilized attitude motions about three axes are so small in amplitude and erratic in phase and period that it is often not possible to distinguish between actual oscillations and sensor system noise and inaccuracies. The librational motions of the spacecraft observed during the remainder of the nearly one-week period of time with the damper disabled are essentially similar to the motions displayed in Figure 3. Based upon the results of two experiments with RAE-I, each nearly one week in duration and separated in time by six months, it is anticipated that non-deployment (or full retraction) of the RAE-B libration damper will result in a very protracted small increase in attitude motions. It may well require more than one or two months for motions to increase by 5 degrees in amplitude. Consequently, there is little or no risk in performing this dynamics experiment.

Experiment 2: Partial Retraction of Single Boom

This experiment involves partially retracting a single boom comprising the lower Vee-antenna to a pre-selected length so as to induce moderate amplitude librational disturbances. A lower boom is preferred, assuming that the initial deployments occur nominally and without the creation of force-free boom deformations (warpages), so as to minimize disturbances to radio observations of celestial sources by the upper Vee-antenna. The length of partial retraction would be determined by pre-experiment computer simulations of the spacecraft dynamics, and probably would exceed 30 meters but be less than the 65-meter partial single boom retraction performed utilizing the RAE-I spacecraft. This experiment would not be initiated unless the spacecraft dynamical behavior consisted of steady-state small amplitude attitude motions. Furthermore, this experiment, as well as the succeeding experiments described below, are to be deferred until such time in the RAE-B mission lifetime as the scientific objectives are considered achieved or nearly so. This period of time nominally is not expected to exceed one year from the time of attaining full mission status in lunar orbit. The current proposed experiment differs in two major respects from the single boom partial retraction performed utilizing RAE-I. In the current experiment, the damper boom is to be maintained in the retracted configuration (in accordance with Experiment 1 described above), whereas in the 1971 dynamics experiment

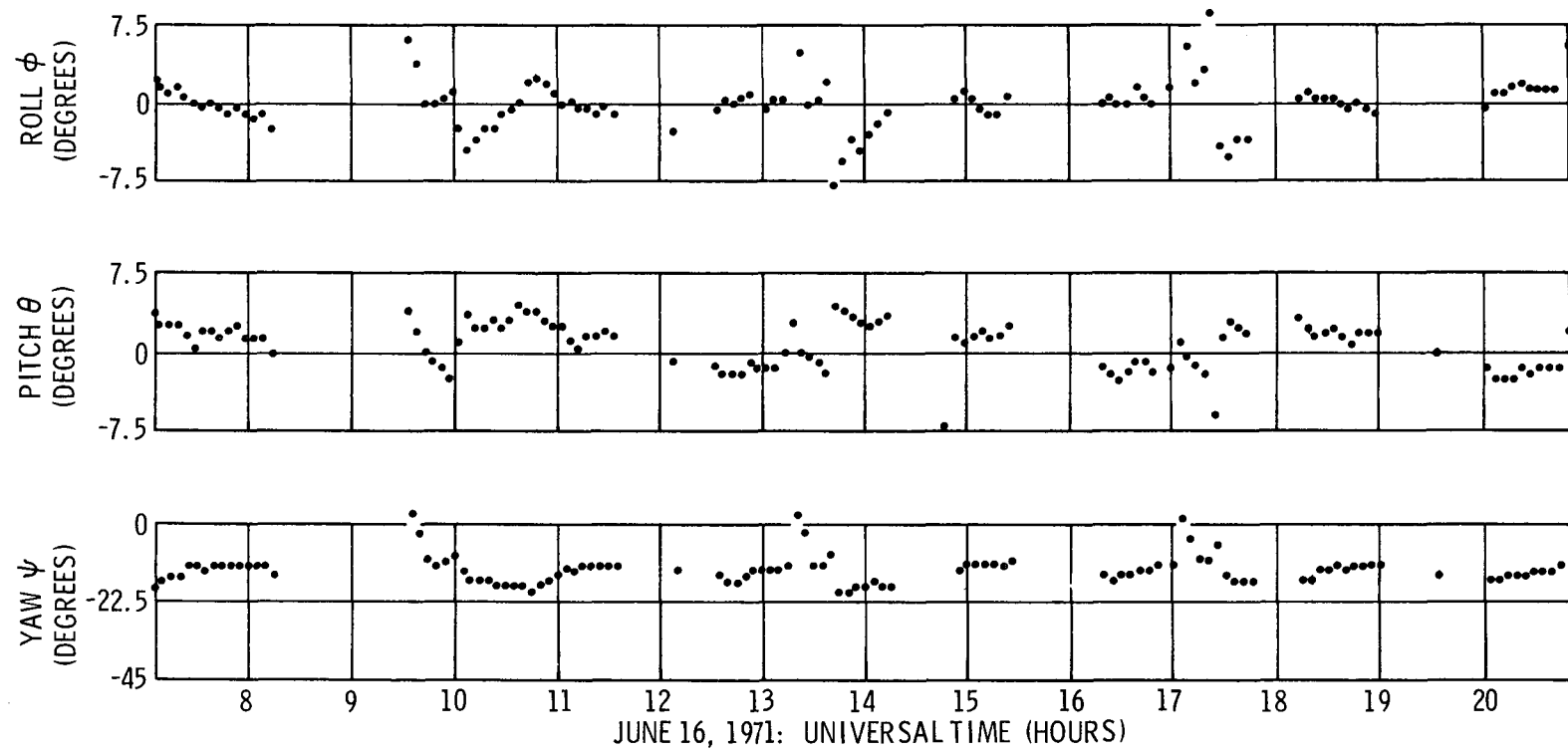


Figure 3. RAE-I Spacecraft Central Hub Attitude Librations During Damper Clamping Dynamics Experiment in Partial Solar Shadowing

the damper remained in active status throughout (refer to Table 1). Secondly, in the current proposal, the primary boom is to remain partially retracted for a period of one to six months; by comparison, the earlier experiment terminated after one week.

The purpose of the single boom retraction experiment is to provide a means for long-term observation of the spacecraft dynamics at moderate amplitude librational motions in the complete absence of damper action and with an asymmetrical spacecraft configuration. Assuming that the damper booms remain in the retracted position, the asymmetry of the configuration will be planar (due to the elimination of the yaw bias angle, as explained previously) and thus differ somewhat from the asymmetrical configuration present in the RAE-I single boom retraction experiment. In particular, this dynamics experiment will provide a method for estimation of the solar pressure effects on an asymmetrical configuration, as well as an indication of the need, or lack thereof, for damper action at moderate librational amplitudes. The study of solar pressure effects requires long-term observation in order to permit the relative geometry of the orbital plane and the sunline direction to vary appreciably over the course of investigation. The relative geometry changes due to the precession of the orbital plane in inertial space, but this is a slowly varying phenomenon. For this reason and others, a time scale of several months is suggested for the current experiment. Again, if attitude librations are observed during the experiment to exceed pre-selected angular bounds, then the libration damper may be deployed to improve the dynamical situation by decreasing the amplitude of the motions.

The results from the single boom partial retraction dynamics experiment performed with the RAE-I spacecraft show that the retraction excited moderate librational motions. The attitude librations immediately following the retraction period, as shown in Figure 4, have maximum amplitudes of about ± 10 degrees in pitch and about ± 15 degrees in yaw, with considerably smaller motions in roll. These oscillations underwent significant reduction during the first several hours following retraction due to the effectiveness of the on-board damper system. In the proposed experiment with RAE-B, it is expected that the retraction will excite moderate amplitude librational motions of ± 10 to ± 20 degrees, primarily in the pitch and yaw modes. Since the damper will be maintained in the retracted position, these motions will persist for a long duration without substantial reduction, except possibly for the effects of structural damping. It is also expected that the attitude motions will induce fairly large boom flexures and that the boom length asymmetry will result in a shift in the pitch axis equilibrium value, as was observed during the RAE-I single boom retraction experiment. Based upon the previous experiment experience with the RAE-I spacecraft and the ability of the computer simulations to predict dynamical behavior in advance, the risk level of performing this dynamics experiment is believed to be fairly low.

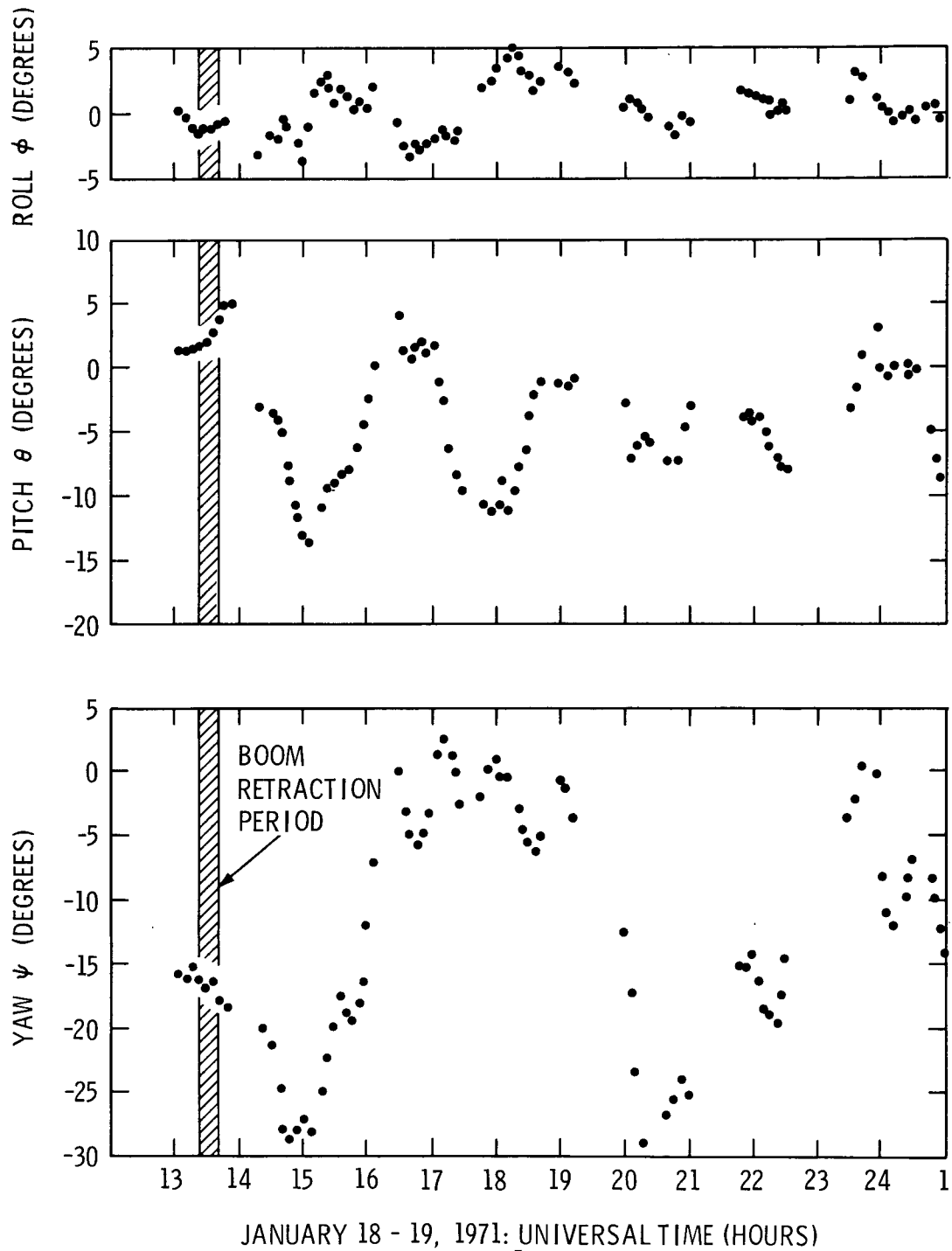


Figure 4. RAE-I Spacecraft Central Hub Attitude Librations During Lower Boom Partial Retraction Dynamics Experiment with Active Damper

Experiment 3: Full Re-Deployment of Single Boom

This experiment consists of the re-deployment to full 230-meter length of the single boom of the lower Vee-antenna which was partially retracted during the previous experiment. Prior to initiating the boom extension operation, it may prove necessary to deploy the damper booms in order to reduce the librational motions remaining from the performance of the preceding experiment to amplitudes which are satisfactory as initial conditions for the deployment. However, it is not anticipated that such damper deployments will in fact be required. The decision as to the advisability of utilizing the damper in advance of the current experiment will be based upon the spacecraft dynamical behavior at the time (i.e., the residual motions from the retraction experiment) and the results of the computer simulations of the dynamics of re-deployment. In any event, the initiation time of boom deployment will be selected with great care so that the phasing of this change in spacecraft moments of inertia will reduce residual librations in deadbeat fashion. It is presumed that the damper will be maintained during and following the boom re-deployment in an inactive status, either in a retracted position or else in a clamped condition if deployed to assist in obtaining proper initial amplitudes.

The purpose of this single boom re-deployment experiment is to demonstrate the feasibility of attaining small amplitude motions by proper timing of boom length adjustment operations, in this case typified by boom extension. This experiment will provide a substantial test of the predictive capability of the computer dynamics simulations with regard to the phasing of active control operations designed to influence subsequent spacecraft dynamical behavior. Also, the possibility of long-term observation of the satellite dynamics with initial librational motions of moderate amplitude following the boom re-deployment in the absence of damper action will be provided by this experiment. It will be of interest to compare the observations in the post-deployment symmetric configuration with those of the preceding experiment involving array asymmetry.

Results from the single boom re-deployment dynamics experiment utilizing RAE-I are in this case particularly relevant since the damper was de-activated just prior to the boom extension and maintained in that status for the following 29 hours. Figure 5 displays the central hub attitude motions immediately following the boom re-deployment period, and Figures 6 and 7 continue the time history of attitude librations in sequence during the entire 29-hour interval of damper clamping and just beyond. It is seen that the motions in roll remained small throughout the entire interval, and that, as expected, the re-deployment excited a pitch libration of about the same moderate amplitude (approximately ± 10 degrees) as in the single boom retraction experiment. Unlike the post-retraction motions, the amplitude of the pitch libration did not noticeably decrease immediately; this

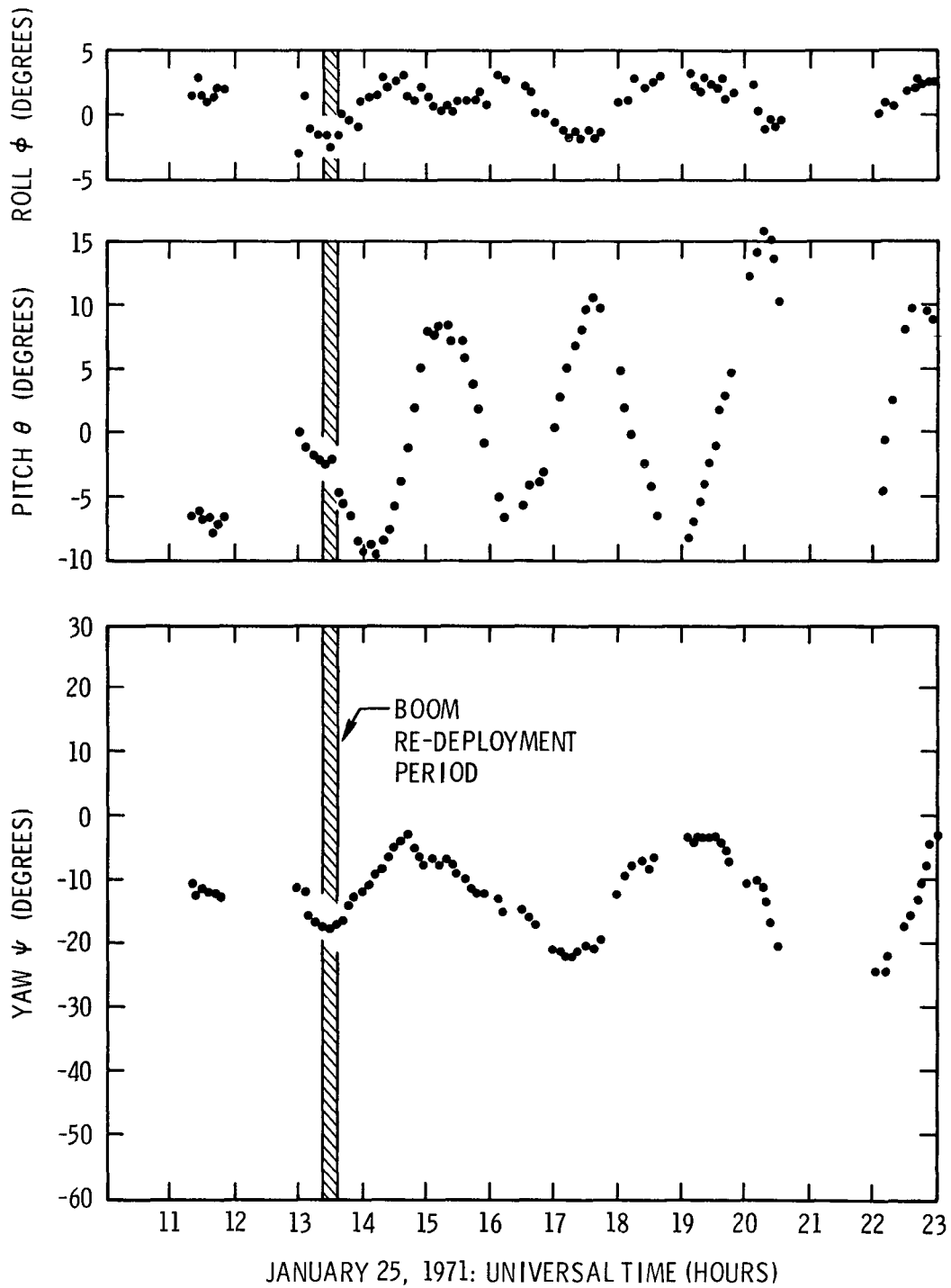


Figure 5. RAE-I Spacecraft Central Hub Attitude Librations Following Lower Boom Full Re-Deployment Dynamics Experiment with Damper Clamped

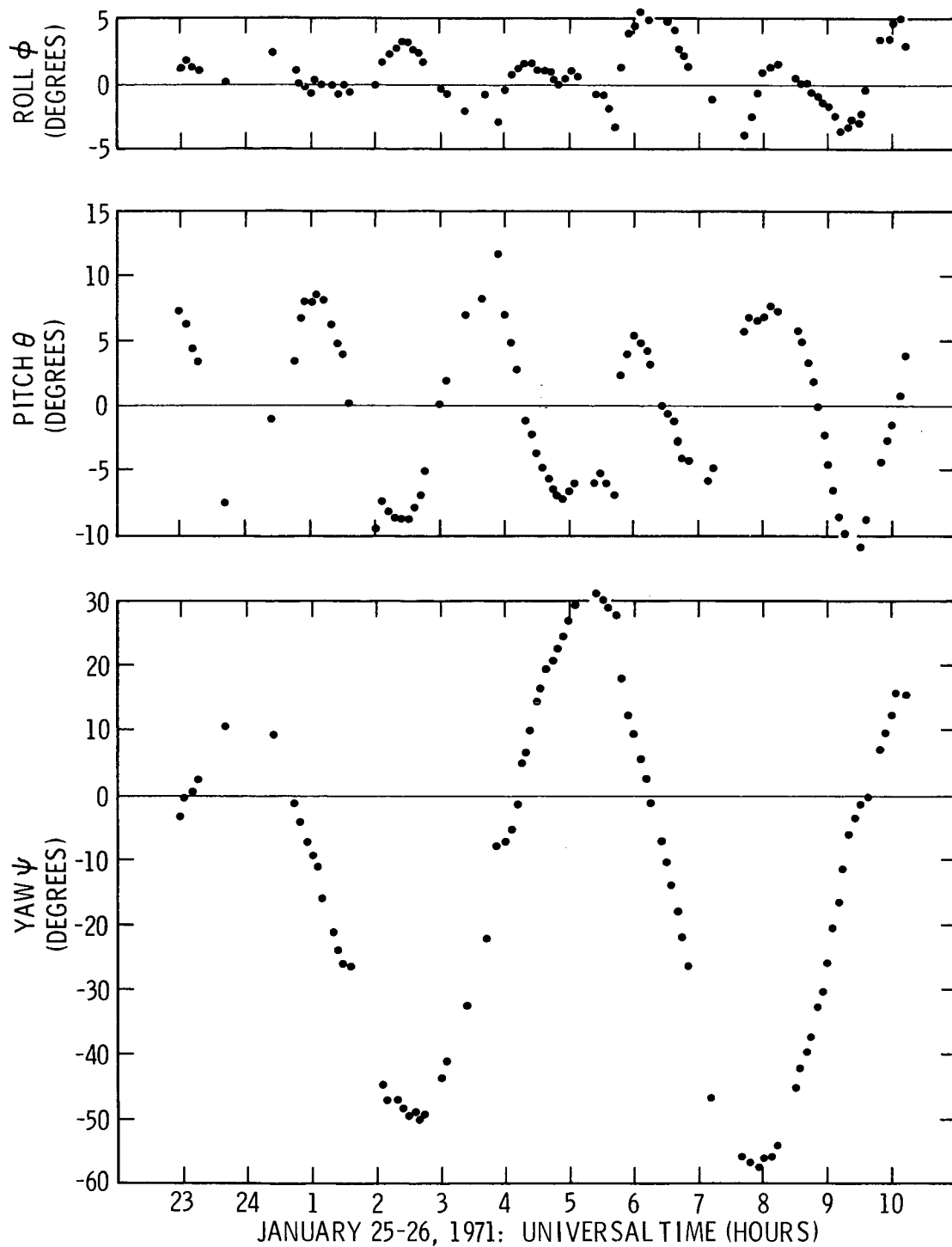


Figure 6. RAE-I Spacecraft Central Hub Attitude Librations Half Day After Lower Boom Full Re-Deployment Dynamics Experiment with Damper Clamped

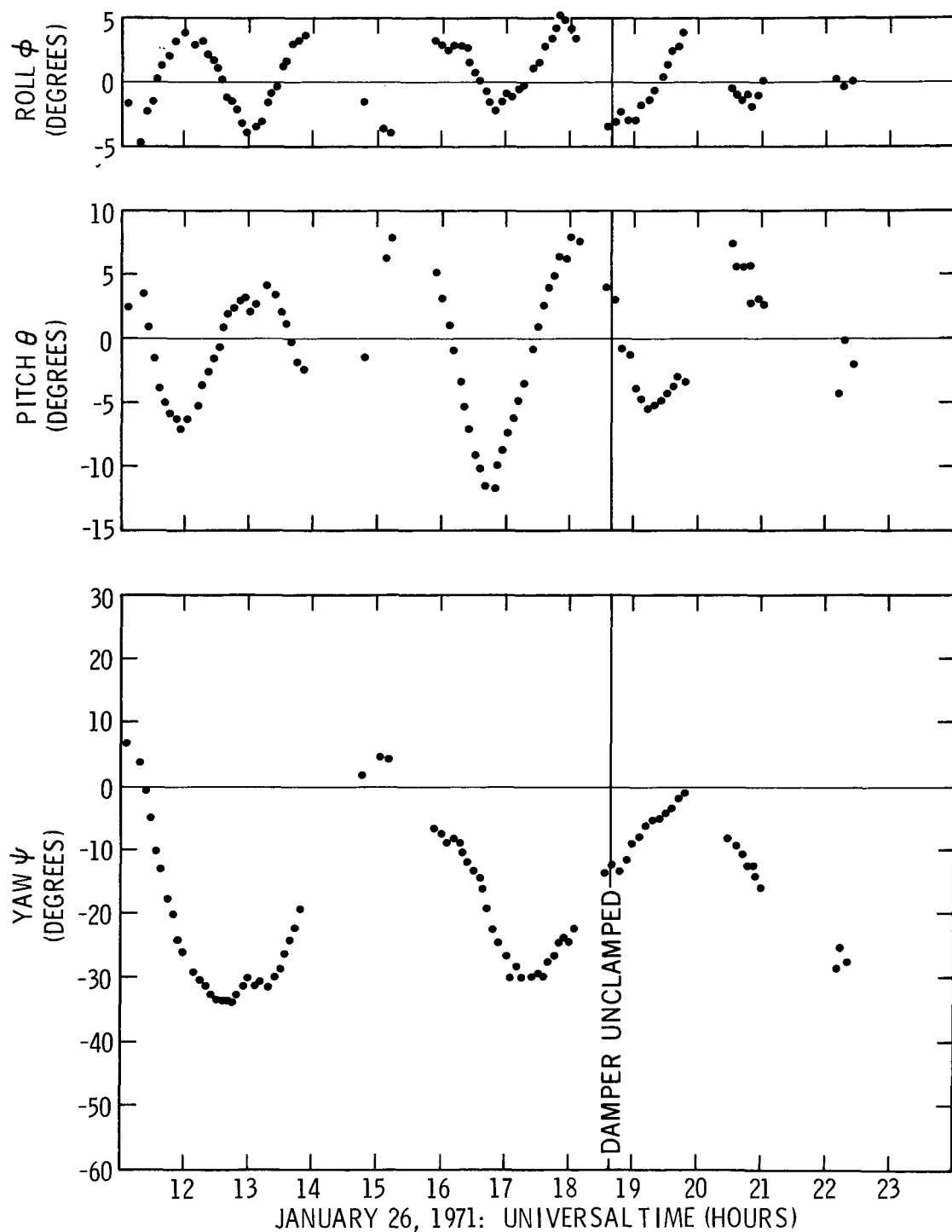


Figure 7. RAE-I Spacecraft Central Hub Attitude Librations One Day After Lower Boom Full Re-Deployment Dynamics Experiment with Damper Activated as Shown

lack of attenuation is directly attributable to the fact that the damper was inactive in the post-deployment interval, although active in the post-retraction period. However, the most significant motions following boom re-deployment occurred in the yaw mode. A yaw libration developed immediately after deployment and amplified dramatically to a maximum of almost 90 degrees in peak-to-peak amplitude after 18 hours (as shown in Figure 6). The yaw motions then decreased at about the same rate as the amplification, and, by the time of damper activation, the oscillations in yaw had decreased to about ± 15 degrees. The amplitude and the frequency of the observed yaw motions were predicted quite accurately by computer simulations of the spacecraft dynamics conducted prior to the experiment (References 3 and 5). The yaw augmentation is believed to have occurred as the result of non-linear coupling between the pitch and yaw modes of oscillation. The fact that RAE-I is the first artificial satellite known conclusively to have demonstrated this phenomenon in orbit is regarded as one of the more significant results of the series of dynamics experiments conducted to date.

As far as the implications of these dynamical measurements of RAE-I behavior for the proposed re-deployment experiment to be conducted with RAE-B, it is worth noting that the observed motions, although large in amplitude, were at all times bounded and did not lead to loss of gravity-gradient capture about any attitude axis. Equally significant is the fact that the divergent motions had peaked and were in the process of decreasing toward equilibrium even before the damper was activated. In the proposed experiment with RAE-B, it is anticipated that the boom re-deployment operation will excite moderate amplitude librational motions of ± 10 to ± 30 degrees, primarily in the pitch and yaw modes. The coupling phenomenon will permit the transfer of energy between librational modes of motion, perhaps in a cyclical fashion. These motions may persist for a long duration, without substantial reduction, in the absence of damper action. However, careful phasing of the re-deployment operation will provide maximum bounds on the motions and reduce the possibility of rotation about any attitude axis. The predictive capabilities of the computer simulations and the previous experiment experience with the RAE-I spacecraft indicate a reasonably low level of risk for this dynamics experiment as well.

Experiment 4: Partial Retraction of Two Booms

This experiment involves simultaneously partially retracting the two booms comprising the lower Vee-antenna to a pre-selected length so as to induce moderate to large amplitude librations. Retractions of the lower booms are preferred, as in Experiment 2, in order to avoid use of the Vee-antenna most critical for radio observations. This assumes, of course, that Experiments 2 and 3 have been performed previously in nearly nominal fashion. The length of partial retraction will be based upon the outcome of computer simulations of the spacecraft

dynamics conducted prior to the initiation of the current experiment. An approximate value for the length of retraction is 20 meters, somewhat less than the 30-meter partial double boom retraction performed with RAE-I, since the damper is assumed inactive in the proposed experiment. Prior to commencing retractions, small amplitude attitude motions are required. It is a possibility that in order to reduce the librational motions remaining from the performance of the preceding experiment, damper boom deployment may be necessary, but this is considered relatively unlikely. At any rate, the damper will be inactive, either retracted or clamped as appropriate, during and following the double boom retractions. The current experiment differs in two major respects from the double boom partial retraction performed previously: (1) the damper is to remain inactive for a period far exceeding the initial 48 hours utilized in the 1971 experiment (see Table 1), and (2) the two booms are to remain partially retracted for a period far exceeding the 8-day interval utilized previously, viz., a period of one to six months is contemplated.

The double boom partial retraction experiment will permit extended observations of the spacecraft dynamics at moderate to large librational amplitudes in the absence of damper energy removal. The configuration during this experiment is described as semi-symmetric, as contrasted with the purely asymmetrical condition present in the single boom retraction experiment. This terminology derives from the fact that the boom lengths within the upper and lower Vee-antennas are equal, but the boom lengths differ between Vee-antennas. Assuming that the damper booms remain in the retracted position in accordance with Experiment 1, the semi-symmetric configuration will be planar, and again will differ somewhat from the semi-symmetric but non-planar (due to the presence of a yaw equilibrium bias) situation encountered in the analogous RAE-I dynamics experiment. The current experiment will provide a further test of the requirement for damper energy removal at moderate librational amplitudes over a long-term interval. If attitude motions diverge during the experiment beyond pre-selected angular bounds, then the on-board libration damper may be deployed to assist in regaining dynamical stability.

Results from the double boom partial retraction dynamics experiment performed with the RAE-I spacecraft show that the retraction excited moderate librational motions, somewhat smaller in amplitude than those observed during the single boom re-deployment experiment. The attitude librations immediately following the double boom retraction period, as shown in Figure 8, have maximum amplitudes of about ± 10 degrees in pitch, the beginnings of increasing yaw motions, and negligible motions in roll. The increasing librations in yaw developed over a longer time span than during the single boom re-deployment and reached a smaller maximum amplitude, viz., the peak motions of about ± 35 degrees in yaw occurred some 30 hours after the retraction operation. The peak amplitudes

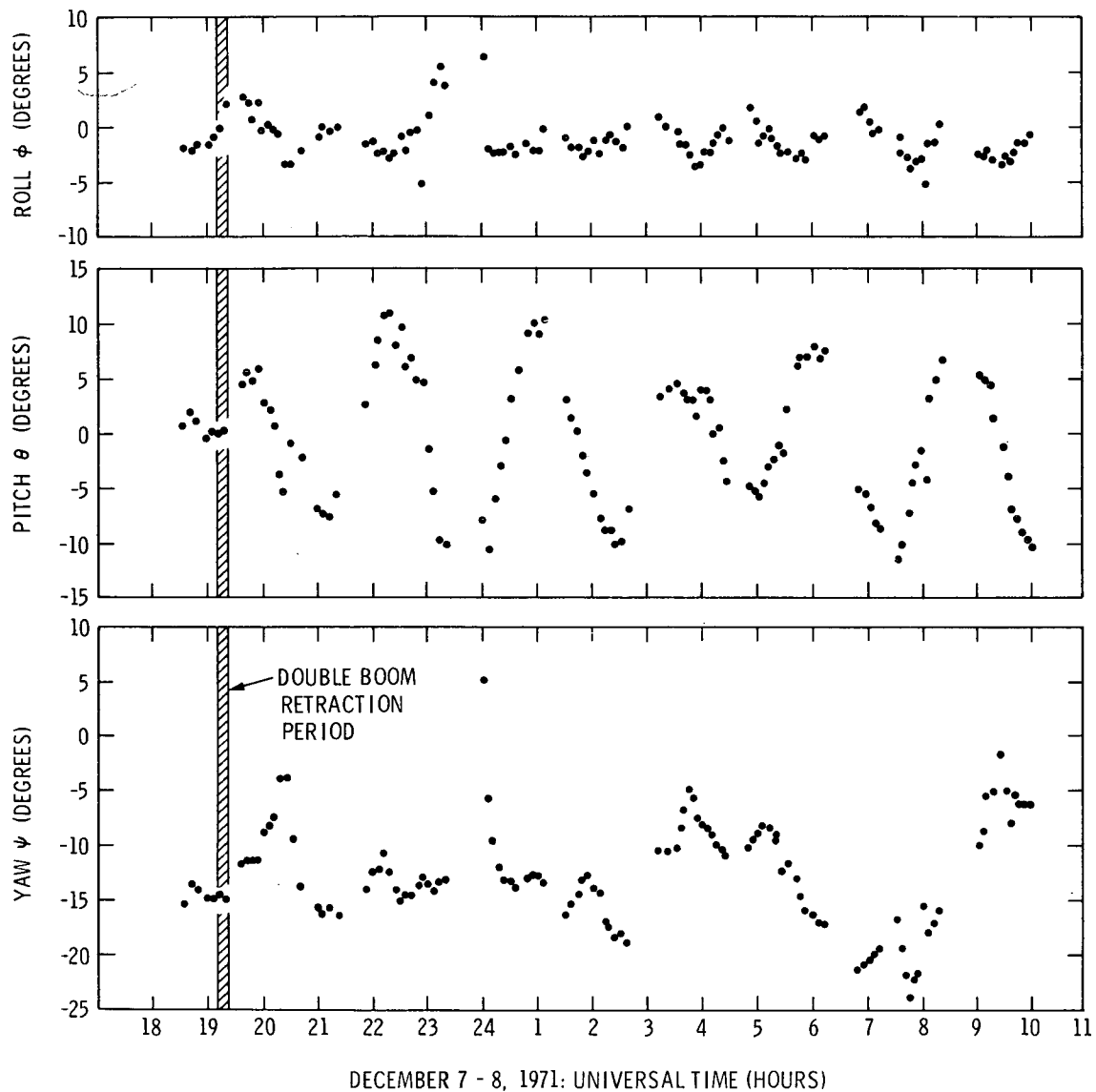


Figure 8. RAE-I Spacecraft Central Hub Attitude Librations Following Lower Double Boom Partial Retraction Dynamics Experiment with Damper Clamped

occurred during the clamped damper interval; in fact, at the time the damper was activated, motions in yaw had attenuated to ± 12 degrees. This reduction in motion amplitudes during the inactive damper period is again significant as it relates to the anticipated behavior during the proposed double boom retraction experiment. It is expected that the double retraction will excite moderate to large amplitude librations of ± 10 to ± 40 degrees, primarily in pitch and yaw. The

motions will remain bounded in amplitude, and the spacecraft will remain gravity-gradient captured about all three axes. The coupling between oscillatory modes will result in long-duration motions, again without substantial reduction while the damper is inactive. In the case that librations diverge beyond pre-selected angular bounds, the damper may be utilized, as mentioned above, in a contingency situation. However, this possibility is considered remote, and the current experiment involves no greater risks than those experiments described previously.

Experiment 5: Full Re-Deployment of Two Booms

This experiment consists of the re-deployment to full 230-meter lengths of the two lower booms which were partially retracted in Experiment 4. If necessary, the damper booms will be utilized to reduce residual librational motions from the partial double retraction experiment in order to achieve proper initial conditions for re-deployment. Once again, this possibility is considered an unlikely contingency, and its necessity will be judged on the basis of existing dynamical motions at the time in conjunction with the predictions of computer simulations of the deployment dynamics. The phasing of the boom deployments will be carefully chosen so as to reduce residual librations by the deadbeat method. The damper is to be maintained in an inactive status during and following the boom re-deployments, even if used to obtain proper initial amplitudes.

This double boom re-deployment experiment will further demonstrate the capability of reducing dynamical motions through properly timed boom length adjustment operations. Such active control of the spacecraft dynamics will provide a further substantial test of the computer dynamics simulations. The post-deployment dynamical behavior of the spacecraft will be compared with that observed in the post-deployment period of Experiment 3 involving a single lower boom.

It is expected that the boom re-deployment operations will excite moderate amplitude librational motions of ± 10 to ± 30 degrees, primarily in the pitch and yaw modes with possible coupling between these modes. Proper phasing of the re-deployment operation will reduce the possibility of rotation about any attitude axis to nearly zero. The results of the RAE-I double boom re-deployment operation included the typical initial pitch libration of just under ± 10 degrees. However, a large amplitude yaw libration divergence was not experienced in that experiment as was the case in the single boom experiment post-deployment interval, apparently because of damper action in the double boom post-deployment period. Since the damper will be de-activated in the proposed experiment, the post-deployment motions may include a temporary amplification in the yaw libration mode and moderate amplitude motions may persist for a long duration. Nevertheless, proper execution of the re-deployment operations will provide bounds on the motions, and the risk involved is considered at a low level.

Experiment 6: Spacecraft Inversion

This experiment will consist of a 180-degree rotation about the pitch axis, resulting in an inversion of the spacecraft, or, equivalently, in an interchange of the upper and lower Vee-antennas. The method to be employed is essentially identical to that already utilized in the RAE-I inversion of 1972, as illustrated in Figure 1 and briefly described in the introductory section of this paper. An inversion of the RAE-B spacecraft may be achieved by the proper phasing of a retraction and a later re-deployment of the primary antenna booms. The simplest technique for accomplishing a 180-degree pitch rotation, as illustrated schematically in Figure 9, involves a single retraction of all four main booms simultaneously followed, after an appropriate coasting interval, by a re-deployment back to full lengths of all four booms simultaneously. The main advantage of this method, as opposed to other possible inversion methods (Reference 10), is simplicity and short total execution time. In particular, this method requires the minimum number of operations of the on-board retraction/deployment motors, thus minimizing the probability of encountering a motor anomaly during the procedure. Furthermore, this method was utilized in the RAE-I inversion performed on October 31, 1972 with the timing and length parameters as indicated in Figure 9. The re-deployment of all main booms is initiated based upon real-time pitch angle data, rather than by a pre-determined pitch rotation interval, in advance of achievement of full inversion. If re-deployments are begun at a pitch angle of 173 degrees (as in the RAE-I operation in October 1972), then a full 180-degree pitch rotation occurs at approximately the same time that full boom lengths are attained. As indicated in Figure 9, the boom extension rates are greater than the boom retraction rates, and this information must be factored into the operational plan for inversion. The libration damper must be inoperative during the entire inversion procedure from prior to initiating the boom retraction operations until after the booms are fully re-deployed and inversion completed. Only if necessary to assist in the RAE-B post-inversion recovery interval will the damper be activated at some later time. Assuming proper phasing of the inversion operations, particularly the start of re-deployments, such damper usage will not be required.

An inversion of the RAE-B spacecraft array, resulting in an interchange of the upper and lower Vee-antennas, would permit an independent verification of radio astronomy observations made during the first portion of the RAE-B mission by an essentially "new" antenna receiver. Since the orbital trajectory of the spacecraft is unaffected by an inversion maneuver and the local orientation following a pitch rotation is indistinguishable from the pre-inversion orientation, the spacecraft array would continue to scan that portion of the celestial sphere that previously had been under investigation. Subsequent precession of the orbital plane of the satellite in combination with orbital revolution will permit coverage of all

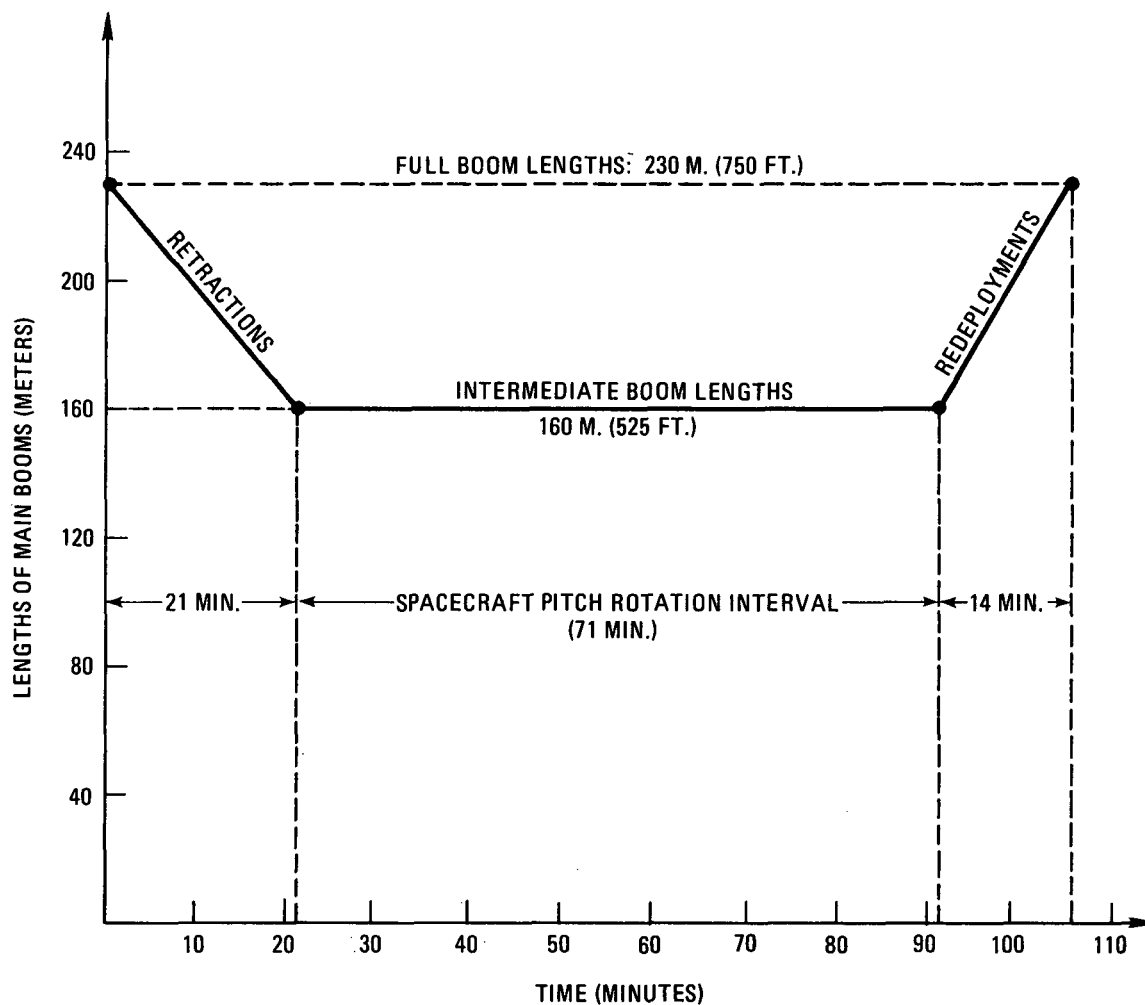


Figure 9. Phasing of Spacecraft Inversion Operations
(RAE-I Spacecraft; October 31, 1972)

celestial sources observed with the original antenna receiver. An inversion operation would also be valuable from the standpoint of providing dynamical data with which to improve the estimations of such spacecraft mechanical parameters as the Vee-antenna apex angles and possible force-free boom warpage deformations. Such estimations result from parameter variations performed to obtain a best fit to the dynamical observations, and the estimations are more accurate

when the dynamical data involve large amplitude attitude librations and boom flexures such as occur during an inversion operation.

Results from the RAE-I inversion maneuver demonstrate that the method is entirely feasible. Figure 10 displays the well-behaved pitch rotation which required approximately 100 minutes, including portions of the boom length change operations. Figures 11 and 12 illustrate the spacecraft attitude librations about all three axes during and following the inversion operation (note the non-linear pitch ordinate axis in Figure 11). The inversion maneuver resulted in moderate amplitude librational motions of about ± 8 degrees in pitch (centered about the 180-degree inverted equilibrium position) and ± 18 degrees in yaw, with minor motions in roll. These maximum amplitudes occurred immediately after the boom re-deployments, and the motions very rapidly attenuated to near steady-state values, as shown in Figure 12. Most significant is the fact that gravity-gradient capture about the inverted position was immediately re-established upon attainment of full antenna boom lengths. In the proposed spacecraft inversion with RAE-B, it is expected that the post-inversion motions in yaw will be of smaller amplitude than those shown in Figure 11. This is because of the fact that, in the absence of deployed damper booms, the spacecraft will rotate entirely within the pitch plane. Such rotation is another consequence of the planar mass distribution in the case of undeployed, or fully retracted, libration damper booms. The RAE-B post-inversion motions in pitch will be comparable to those shown in Figure 11, assuming that the phasing of the boom re-deployment interval is equivalently accurate to that which occurred in the RAE-I maneuver. Of course, the absence of damper energy removal in the RAE-B experiment will result in long-duration motions and some coupling between oscillatory modes without the substantial reduction in amplitudes displayed in Figure 12. In a contingency situation, the damper is again readily available for use in attenuating motions to steady-state conditions. Although this possibility is considered remote, the spacecraft inversion experiment involves a moderate level of risk. However, the chances of achieving gravity-gradient capture in an inverted position are deemed excellent in view of the RAE-I history.

Experiment 7: Gravity-Gradient Controls

This experiment, to be performed subsequent to the successful conclusion of the previously described experiments, is of more general character and dependent upon RAE-B mission conditions that exist at the time. Two possible forms that an experiment in gravity-gradient controls might assume are the following: (1) a 180-degree rotation about the yaw axis, resulting in a reversion of the spacecraft, and (2) an increase in pitch motions of the spacecraft, resulting in several revolutions of pitch motion per orbital period, i.e., a pitch spin. A reversion in yaw could be performed by properly phased antenna boom retractions and extensions

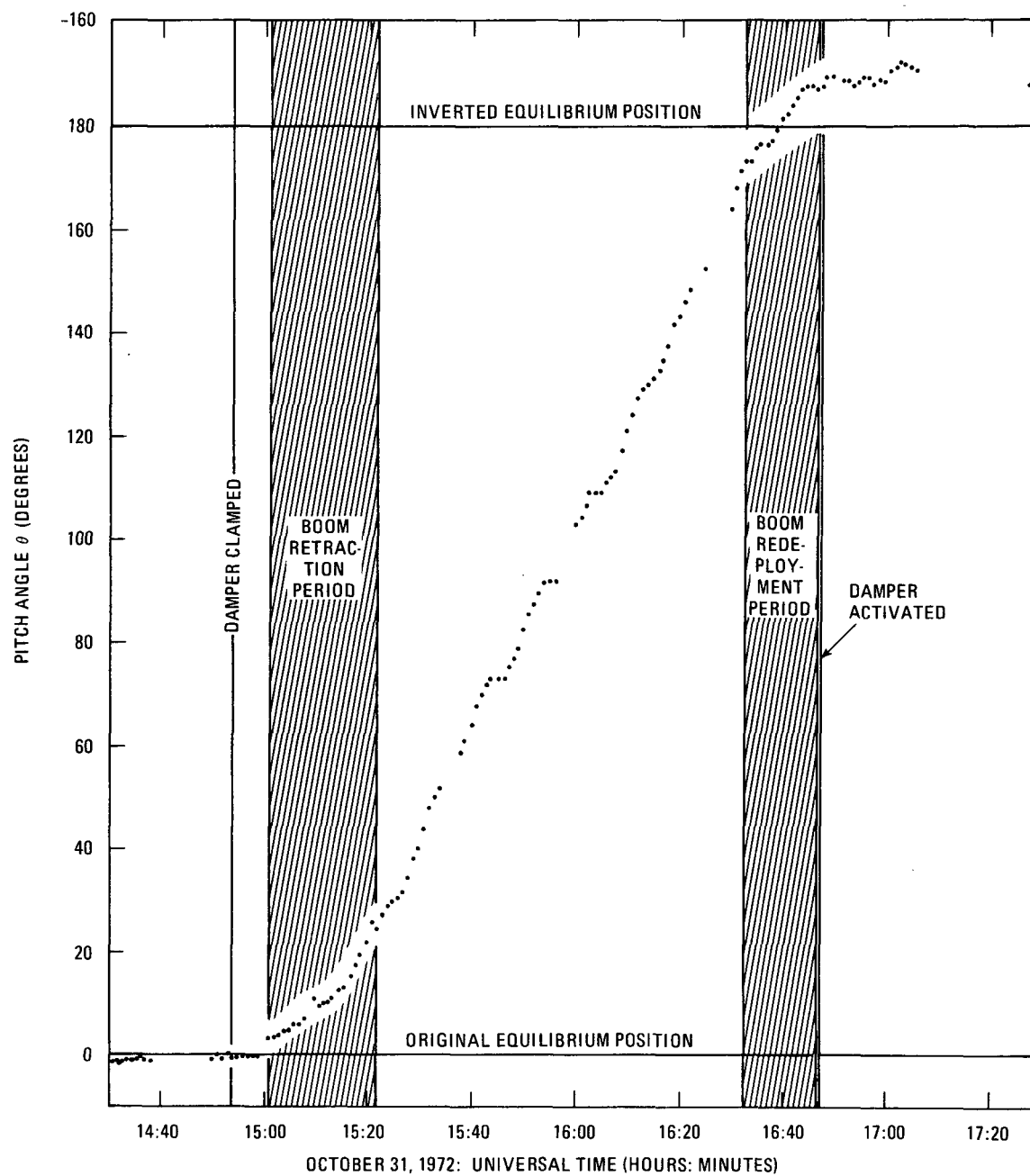


Figure 10. RAE-I Spacecraft Central Hub Pitch Attitude During Inversion Operation

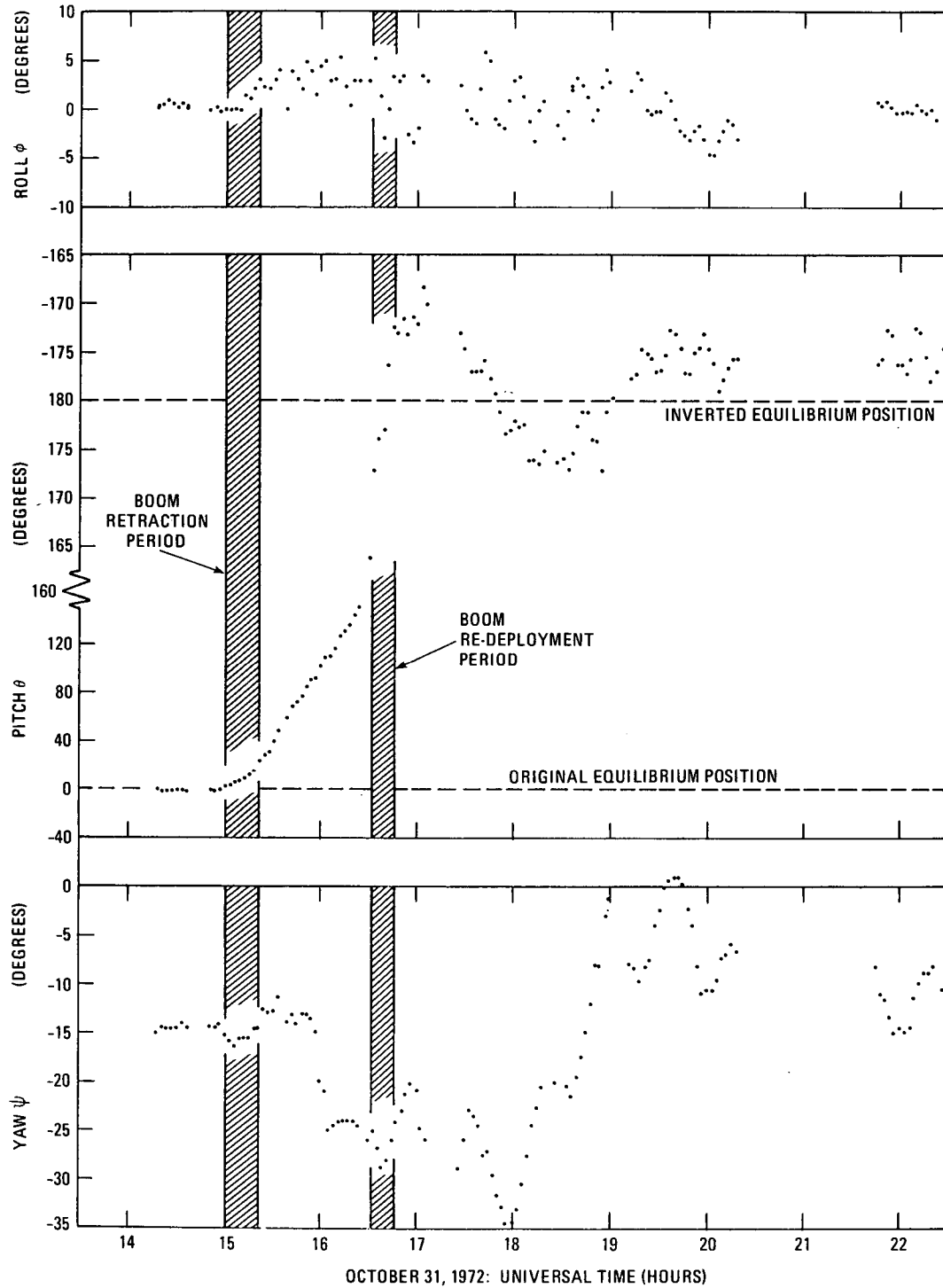


Figure 11. RAE-I Spacecraft Central Hub Attitude Librations During and Following Inversion Operation

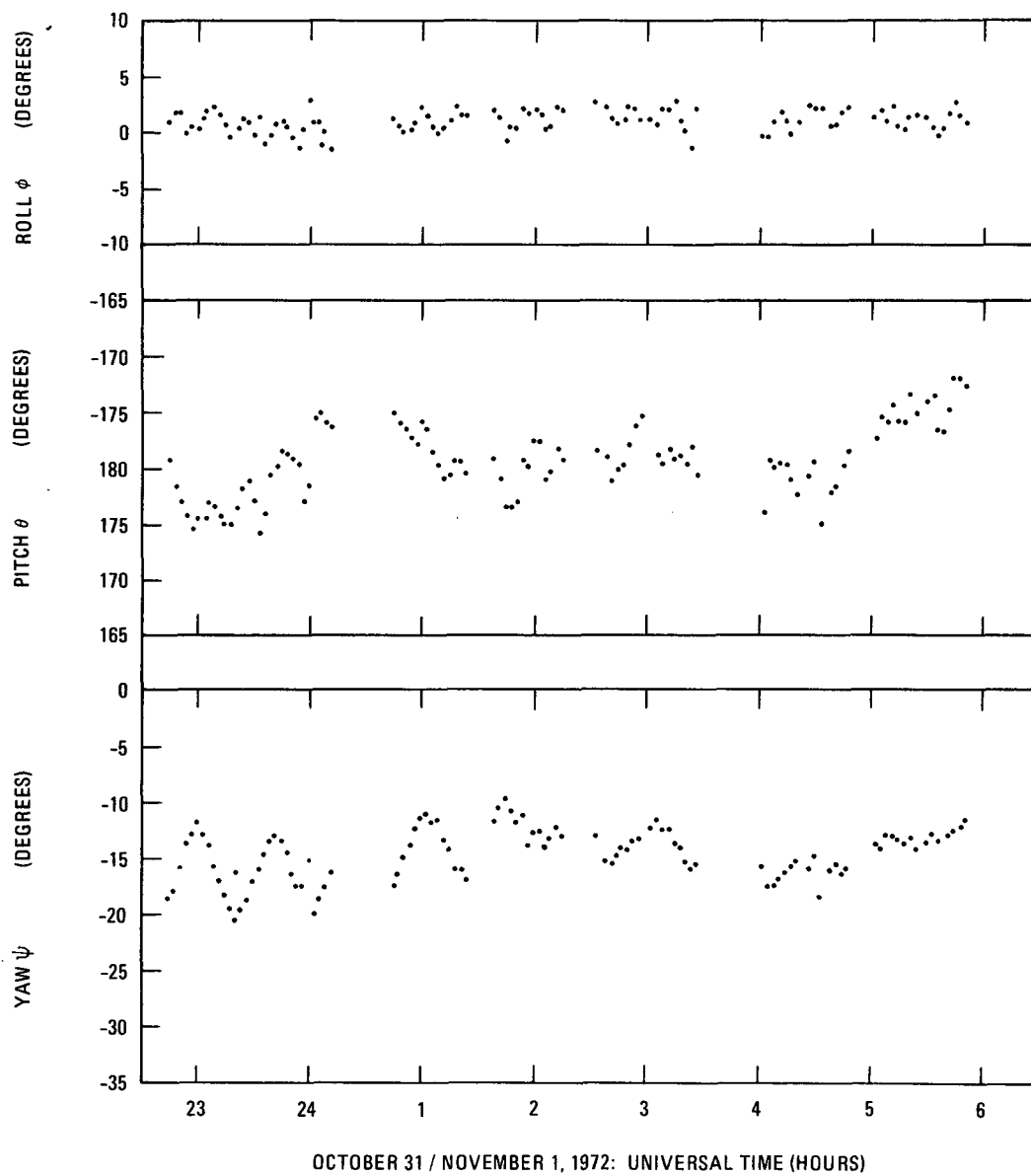


Figure 12. RAE-I Spacecraft Central Hub Attitude Librations Following Inversion Operation

arranged to result in asymmetrical spacecraft configurations in which the attitude librational motions would strongly couple into the yaw mode. Such a strong coupling into the yaw mode was exhibited during the single boom re-deployment dynamics experiment performed with the RAE-I spacecraft, as shown in Figure 6. A well-calculated modification in the boom length or timing parameters would readily produce a reversion or "flip" about the yaw axis. By contrast, a pitch spin may be effected by properly phasing main boom retractions and extensions arranged so as to produce symmetrical spacecraft configurations. In the symmetrical case, the attitude librational motions remain primarily in the pitch mode in which they are initially induced by deliberate changes in the moments of inertia about the pitch axis. By properly modifying the boom length and timing parameters shown in Figure 9, as applied during the RAE-I inversion operation, consecutively occurring inversions, in which gravity-gradient stabilization is not re-attained, may be produced. In this way, the gravity-gradient forces are utilized to attain a pitch spin of the spacecraft through a "gravity-gradient pump" mechanism, as suggested in Reference 2.

The objective of either of the two exercises cited in this experiment is to demonstrate the potential uses of active control systems on spacecraft of the RAE type to proposed very large array spacecraft of the future. Most current concepts require the expenditure of considerable control fuel for the spin-up of such large arrays. It is quite likely that techniques employing only the on-board electrical power to produce boom length changes in conjunction with the small forces of the gravitational field could be used for the control and spin-up of future large space arrays.

The fact that the damper booms may be retracted on the RAE-B spacecraft increases the possibility of achieving a successful pitch spin, because of the planar mass distribution which exists in the absence of damper booms. In order to promote a reversion in yaw, however, the presence of extended but clamped damper booms is desirable. In this case, the yaw bias produced by the damper skewness to the Vee-antenna plane would assist in generating large amplitude yaw motions. Nonetheless, due to the advanced nature of these experiments, the outcome is not as certain as in the first six experiments described previously. One potential problem in particular is that the continuous large deformations induced by a spin in pitch would place a considerable strain on the flexible antenna booms. In view of these uncertainties, it is advisable to defer at least the pitch spin experiment until such time as the RAE-B mission has fulfilled the majority of its scientific objectives in radio astronomy (as described in Reference 1).

OPERATIONAL PROCEDURES

The operational procedures to be followed in conducting the gravity-gradient dynamics experiments in lunar orbit using the RAE-B spacecraft will be similar to those employed during the RAE-I dynamics experiments in Earth orbit (Reference 3). Before each experiment, an extensive and systematic set of computer simulations of the spacecraft dynamics during and following the specific experiment under consideration is conducted. For this purpose, the dynamics models developed prior to the launch of RAE-I in 1968 and refined and improved since that time are utilized. These simulations, in conjunction with the results of simplified analytical techniques, are studied in order to understand and anticipate the dynamical behavior of the spacecraft during the experiment. Limits are established for dynamical motions beyond which point corrective action (such as activation of the damper mechanism) must be undertaken, and a full set of contingency plans is established for non-nominal conditions. An operational sequence of spacecraft commands is tabulated, and permissible attitude libration and timing tolerances or "windows" for each command are formulated.

Following these studies, the dynamics experiment is performed with the associated collection of dynamical data consisting of time histories of the three-axis attitude librations of the rigid central spacecraft hub, of the flexural motions of the main antenna booms, and of the excursions of the damper booms, if utilized. These data are used to monitor spacecraft behavior in a near real-time mode, and later the observational data are reduced to definitive form for post-experiment analyses. In fact, two levels of analysis are performed. In the first level, a visual study of the dynamical data provides a qualitative estimate and a quick overview of most of the major results. The second level of analysis provides quantitative results. For this level, computer simulations are utilized in an effort to determine unobservable initial conditions and to match the in-orbit observations. In this way, the values of certain physical and mechanical parameters, which are most sensitive in a particular dynamics experiment, may be estimated. The final product, of course, will be a report of the experiment observations and interpretations compiled and disseminated for appropriate publication following the conclusion of the experiments.

CONCLUSIONS

A series of six specific gravity-gradient dynamics experiments utilizing the RAE-B spacecraft in lunar orbit has been proposed. Each experiment has been discussed individually as to purpose, description, and spacecraft anticipated dynamical behavior. The experiments will necessarily be preceded by nominal mission events preparatory to achieving full mission status for the RAE-B

spacecraft antenna array. In particular, deployments of the main antenna booms to full lengths by the deadbeat technique are required by nominal mission plans. These operations will determine, to a large extent, the desirability of proceeding with the first dynamics experiment, viz., non-deployment of the damper booms. If dynamical stability conditions following antenna deployments require use of the damper mechanism, the first experiment may be conducted at a later stage of the mission by full retraction of the damper booms. In either event, it is the first dynamics experiment that offers the greatest opportunity for advancing the general understanding of passive three-axis gravity-gradient stabilization and control systems. The five follow-on dynamics experiments are an outgrowth of, and similar in concept to, experiments already performed in Earth orbit utilizing the RAE-I spacecraft. However, there are significant differences in the proposed single and double lower boom operations and spacecraft pitch inversion experiments that contrast with the RAE-I experiment experience. Primary among these differences are the long term duration suggested for the current experiments and the absence of damper action and inertia involved. These distinctions will permit studies of perturbative effects during the current experiments that were not previously possible. A seventh and more general dynamics experiment in gravity-gradient controls is suggested as an optional sequel to the series to be performed if mission conditions warrant.

Each of the proposed dynamics experiments has been examined in detail as to its effect on subsequent spacecraft behavior and especially with regard to the likelihood of unimpaired continuation of the scientific mission of RAE-B. Results from comparable dynamics experiments utilizing the RAE-I spacecraft have been presented when available and applicable. When possible, these results have been extrapolated to conform to conditions that will pertain during the proposed RAE-B experiments. In every case, a substantial amount of concern has been exercised in this preliminary analysis in order to specify and design experiments that will incur minimal risk to the spacecraft structure. For this reason, the first four experiments involving boom length change operations do not affect the upper Vee-antenna elements, which are of primary importance to radio astronomy observations of celestial sources. Furthermore, the relatively short RAE-B dipole antenna would continue its radio astronomy investigations throughout the performance of the dynamics experiments, since this antenna is not adversely affected by attitude librations. Certain of the dynamics experiments that are judged to be of relatively higher risk may be deferred until the scientific objectives of the RAE-B mission have been attained or nearly so. An operational procedure has been outlined which includes extensive and systematic computer simulations and the development of a full set of contingency plans for non-nominal conditions, all prior to execution of each experiment. Finally, in order to attenuate possible attitude librations that exceed pre-determined bounds, the on-board libration damper mechanism may be readily activated by ground

command as a corrective measure. In sum, it would appear highly desirable and timely to undertake during the RAE-B mission a series of gravity-gradient dynamics experiments in lunar orbit such as proposed herein.

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